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Landscape dynamics and human disturbance processes in wetlands in a mining city: a case study in Huaibei, China

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Abstract Wetlands are fragile ecosystems that are sensitive to human activities. In mining cities with high groundwater tables, underground mining, urbanization, and land reclamation cause severe disturbance to wetland landscape patterns, which poses a serious threat to the integrity and sustainability of the regional wetland ecosystems. This paper extracted the dynamic patterns of wetlands in Huaibei, China, from the Landsat TM/ETM remote sensing images with a time duration of 30 years from 1991 to 2021. The land-use transfer matrix and the landscape metrics were used to analyze the dynamic evolution of the wetland landscape patterns in this typical mining city. Afterwards, the human disturbance changes in the wetlands during the past 30 years were analyzed by the human disturbance transformation index (HTI). The correlation between the HTI and the changes in the landscape metrics were analyzed to reflect the influences of different human disturbance mechanisms on the evolution of the wetland landscape patterns. The results indicated that the wetland areas gradually increased with rising human disturbance levels from 1991 to 2021. However, the wetland landscape patterns showed a trend of declining landscape connectivity and fragmentation. The human disturbance levels to the wetlands were found significantly increased from 1991 to 2005 and from 2010 to 2015, and declined from 2005 to 2010 and from 2015 to 2021. The correlation between the HTI and landscape metrics indicates that current ecological restoration planning has limitations in improving the wetland landscape patterns. In the future, it is necessary to formulate systematic wetland landscape patterns restoration planning that covers the overall area according to the evolutionary trend of wetlands.

Keywords Wetland landscape evolution · Mining subsidence area · Landscape pattern · Human disturbance

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Introduction

Globally, coal is the most widely distributed conventional energy source. However, the environmental damage caused by coal mining has long been a challenge for the global mining industry (Worlanyo et al., 2021). Currently, China is the world's largest producer of coal. In 2021, the coal output of China

reached 4.13 billion tons, which accounted for more than half of all coal produced worldwide. More than 95% of coal mines are underground mines in China. Comparing with open pit mines, underground mining has resulted in serious land subsidence and changes in landscape patterns (Dong et al., 2015). It is estimated that every 10,000 tons of coal mined from underground mines will cause 0.2 to 0.33 ha of land subsidence in China (Xiao et al., 2018). According to the current proven coal reserves in China, it is expected that more than 60,000 km^2 of land will subside after all of them are mined (Zhu et al., 2022). The ecological restoration of mining subsidence areas has become a critical environmental issue due to serious environmental damage.

The geographic features of the China coal mines in each district are of great differences, and the environmental problems caused by coal mining are regional in nature. The eastern Huang-Huai region is a major agricultural area in China. The long-term development of agriculture has severely degraded wetlands, and wetlands are among the most vulnerable ecosystems on earth. The remaining wetlands play an important role in maintaining the ecological balance and conserving local biodiversity. Meanwhile, this region is rich in coal resources. The coal fields in this region have multiple and thick coal seams, a high groundwater table, and flat terrain. Underground mining has fractured the overlying stratigraphy, influenced aquifer connectivity, and affected surface flows due to land subsidence (Liu et al., 2021). On one hand, mining activities have the potential risks of changing the runoff of rivers; on the other hand, a large number of mining subsidence wetlands with high depths are formed due to the high underground water table (Dong et al., 2015; Mason et al., 2021). This phenomenon causes the original terrestrial ecosystem to become an aquatic ecosystem (Zhang et al., 2020). In the Ramsar Convention (1999), the negative influences of mining subsidence wetlands were considered. They have also been regarded as a type of artificial wetland in China's wetland classification standard.

Wetlands have significant landscape heterogeneity (Elliott et al., 2020). The evolution of wetland landscape patterns is related to changes in ecological processes such as the hydrological cycle, plant diffusion, and animal migration (Donnelly et al., 2019; Epting et al., 2018). The wetland ecological service function is significantly impacted by changes in landscape patterns (De Pablo et al., 2020; Gaglio et al., 2017). The simulation and analysis of wetland landscape pattern characteristics, changing trends, and disturbance processes have become important topics in wetland science research (Mao et al., 2018). The optimization of landscape patterns has been a key indicator of wetland ecological restoration (Taddeo et al., 2020). In mining cities, landscape pattern evolution due to high-intensity mining and land use is considered to be the main manifestation of human activities affecting the health of wetland ecosystems and the stability of ecological service functions. Recent studies have suggested that the disturbance mechanisms of human activities to wetlands in the mining cities have spatial and temporal differentiation (Dong et al., 2015; Sun et al., 2015). In the early stage of mining, the impact of human disturbance on wetlands is mainly at patch scale, resulting in the instability of wetland patch morphology. The indices of patch number, area, shape, and patch core area change significantly. In the mature stage, the wetland landscape patterns at basin scale undergo significant changes, including fragmentation, reduction of connectivity, and degeneration of river network structure (Marschalko et al., 2014). With the decline of the mining industry, the changing rate of wetlands also decreases. The main objectives of wetland ecological restoration at this stage are to optimize wetland landscape patterns, maintain water balance, and improve habitat quality.

It is possible to determine the driving mechanisms behind wetland landscape evolution by analyzing human disturbance, which can serve as an important decision-making tool for restoring wetland ecosystems. For wetlands, natural factors can cause large-scale spatial and temporal changes that are usually difficult to reverse (Middleton et al., 2017). The temporal and spatial scale of human disturbance in wetlands is restricted, but the disturbance mechanisms are varied. In the mining cities, underground mining is the primary driving force for the evolution of the wetland landscape patterns. Direct impacts include the changes in the surface runoff and the spatial distribution changes in water areas due to drainage, inundation, or reclamation (Dolný & Harabiš, 2012; Mason et al., 2021; Xiao et al., 2022). However, mining is not the only human-induced factor causing wetland landscape evolution. The mining industry promotes the further development of the economy and

society, especially the growth of urban areas. The risk of construction land occupying wetlands rises with the improvement of the urbanization level. The development of cities requires wetlands to provide various ecological service functions, such as mitigating flood damage, regulating climate, and serving as a natural habitat supporting biodiversity (Hu et al., 2018). All of these factors have an impact on how the wetland resources are used. In addition, land reclamation is also an important driving force which has a long-lasting impact on how the wetland landscape changes.

Previous research on the ecological restorations of wetlands in the mining cities with high groundwater tables has focused on the following three aspects: (1) the causes of land subsidence and waterlog processes after coal mining (Li & Zhou, 2020); (2) the changing characteristics of wetland landscape patterns and ecological effects (Hart et al., 2011); and (3) ecological security patterns and ecological risk forewarning (Wu et al., 2021a, b; Zhou et al., 2020). However, quantitative information about the spatial diffusion of human disturbance and its ecological effects is still incomplete. Taking Huaibei as an example, this paper analyzes the spatiotemporal evolutionary characteristics of human disturbance from the rapid development stage to the recession stage of the mining industry. The aims are as follows: (1) the Landsat TM data from 1991, 1995, 2000, 2005, 2010, 2015, and 2021 are used to investigate and analyze the response of the wetland landscape patterns to human disturbance in the mining cities with high groundwater tables; (2) the human disturbance transformation index (HTI) is established to analyze the spatiotemporal evolution of human disturbance; and (3) the correlation between the wetland landscape pattern changes and human disturbance is identified. The results of this study are important for ecological risk assessment and the improvement of wetland ecological restoration planning.

Study area

The Huaibei coalfield (116°23′-117°02′E, 33°16′-34°14′N), one of the 14 largest coal production bases, is located in northern Anhui Province, Huaibei city. This area has a temperate semihumid climate, with an annual average rainfall of 849.6 mm and an average annual evaporation of 918.0 mm. Huaibei is located in the Huaihe River Basin, and all the rivers of Huaibei are the secondary or tertiary tributaries of the Huaihe River. The Xiaosuixinhe Basin and Tuohe Basin are taken as the study areas, with a total area of 1144.74 km^2. This area includes 8 districts: Lieshan, Xiangshan, Duji, Suixi, Liuqiao, Tiefo, Baishan, and Sipu (Fig. 1). The terrain of the study area can be primarily divided into hills and plain areas. The hills in the eastern and northern areas lie at altitudes of 60–400 m. The rest are plains with altitudes of 23.5–32.4 m. The groundwater is mainly quaternary phreatic water and fissure karst confined water, and is present in the mining area with a high groundwater table.

There were 20 coal mines in the study area, of which 18 have been shut down. The earliest coal mine was built in 1958. All coal mines in the study area were underground mines. With the development of the mining industry, Huaibei has gradually developed from a rural to an urban area. The study area is also the most urbanized and densely populated area in Huaibei, where human activities have the most severe impact on the ecological environment. After the 1990s, the mining industry of Huaibei was in a period of rapid development. With the exhaustion of the coal resources, Huaibei was listed as a "resource-exhausted city" by the State Council in 2009. Long-term underground mining has resulted in the formation of five mining subsidence areas covering 17,171.1 ha. Nearly 15% of the study area is mining subsidence area. The submergence depth was approximately 1–3 m. Due to the degradation of terrestrial ecosystems, most water areas have gradually become wetland ecosystems. Land subsidence and waterlogging have caused the destruction of a large number of arable land and residential areas, aggravating land-use conflicts.

Materials and methods

Data source and processing

This study chose 7 Landsat TM/ETM images for 1991, 1995, 2005, 2010, 2015, and 2021 (acquired from the USGS and Geospatial Data Cloud) to extract wetland landscape information. All images were recorded from June to October during the wet season. The images were geometrically registered and
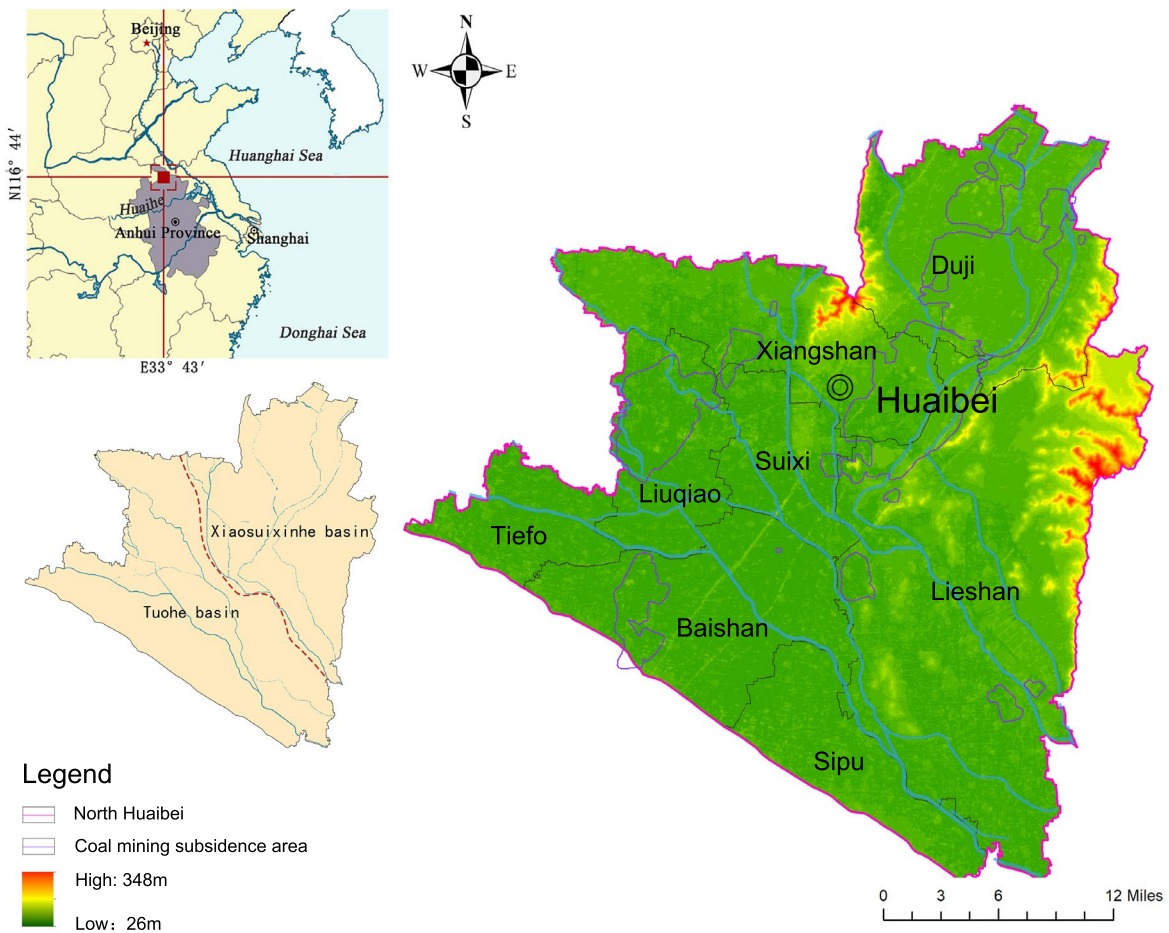
Fig. 1 Location of study area, Anhui Province, China

radiometrically normalized to an acceptable map projection (Orimoloye et al., 2019). According to the land-use classification standard of the Chinese Academy of Sciences, the images were classified into arable land, forestland, grassland, wetland, construction land, and unused land by using supervised maximum likelihood classification techniques. At the same time, according to the Chinese wetland classification standard, the wetlands in the study area were divided into natural rivers, artificial canals, reservoirs, ponds, artificial lakes (composition of urban green space), and mining subsidence wetlands. The topographic maps (1:50,000), wetland resource survey reports (produced in 2000 and 2017), urban blue line protection planning and mining subsidence area distribution maps (produced in 1995, 2005, 2015, and 2020) were used to identify different wetland types. These data were from the Huaibei government. The DEM data of Huaibei were obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn). Finally, the accuracy of remote sensing image interpretation was evaluated by field investigation. The evaluation results indicate that the kappa values of all classification results are higher than 0.85, and the kappa values of wetland classification results are higher than 0.90. With reference to the China national land use remote sensing monitoring results, the average classification accuracy of cultivated land, urban and rural, industrial and mining, and residential land should be more than 85%, and the average classification accuracy of other land use types should be more than 75%. The results meet the accuracy requirements, and they were shown in Fig. 2.

Fig. 2 Landscape patterns of study area from 1991 to 2021
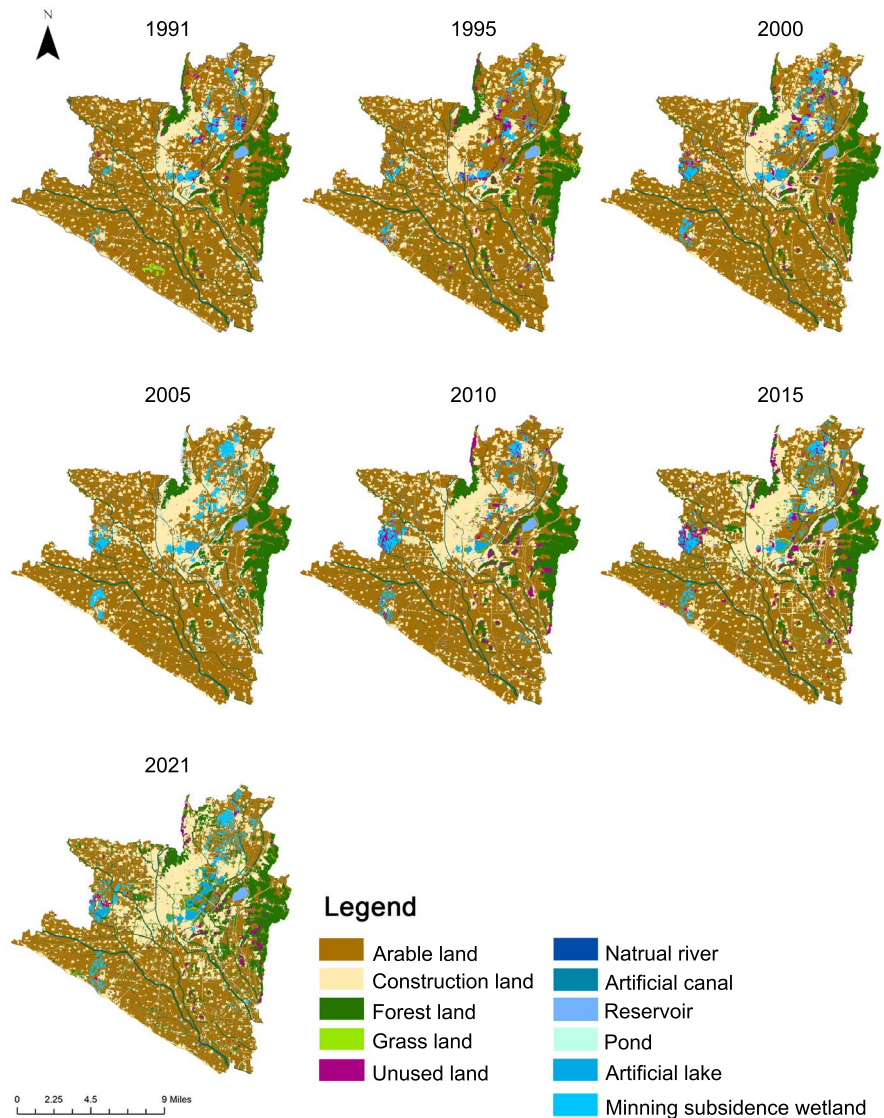
Wetland landscape dynamics

After obtaining the landscape pattern information for different years in the study area, the mutual transformation between wetlands and other land-use types was performed by using a land-use transition matrix (Zheng et al., 2017). The equation of the land-use transfer matrix is as follows:

$$s_{ij} \begin{cases} s_{11}, s_{12}, s_{1n} \\ s_{22}, s_{22}, s_{2n} \\ s_{m1}, s_{m2}, s_{mn} \end{cases} \tag{1}$$

where S_{ij} is the changing area from landscape type i to j in a certain period; m and n are the number of landscape types.

Landscape metrics

Landscape metrics are the quantitative indicators used to reflect the composition of landscapes and the characteristics of spatial allocation (Festus et al., 2020; Imbrenda et al., 2018). There are three types of landscape metrics: patch level, class level, and landscape level, which represent the spatial pattern information of different landscape levels. The results of landscape metrics change with different granularities (Neill et al., 1996). The study area contains a large number of small wetlands and canals. Thirty meters was selected as the optimal granularity in order to avoid the loss of spatial data of small wetland patches (Yang et al., 2021). According to the changing characteristics of wetlands in the study area and research objectives, the number of patches (NP), patch density (PD), and mean patch area (MPA) were chosen to analyze the fragmentation of wetland landscape patterns (Li et al., 2020; Wu et al., 2019). The largest patch index (LPI) was used to reflect the landscape dominance of wetlands. The perimeter area fractal dimension (PAFRAC) was used to reflect the complexity of wetland patch shape. Previous studies have shown that curved patch edges offer more niche or habitat opportunities than straight edges. Connectivity is regarded as an important indicator for monitoring the health of wetlands (Thompson et al., 2019). SPLIT and COHESION were selected to reflect the spatial connectivity of wetland patches (Yan & Niu, 2019). All landscape metrics were calculated by FRAGSTATS 4.2.

Transition of human disturbance

Variations in landscape patterns can provide crucial information on the effects of human activities on landscapes. So that the analysis of landscape transformation processes can reflect the spatiotemporal differentiation of human disturbance (Walz & Stein, 2014). Based on previous studies and the level of human disturbance to different landscape types, all landscape types can be summarized as spontaneous renewal, human regulation, and human domination. The disturbance intensity can be divided into 5 levels (Table 1) (Wu et al., 2021a, b). Spontaneous renewal refers to land-use types in which ecological processes are mainly affected by natural factors and human disturbance is weak. They are often important ecological reserves. Human regulation refers to the evolution of ecosystems under human management and regulation, which has important ecological supply and ecological regulation functions. According to the frequency of human disturbance, it can be divided into two levels. Human dominance means that the formation and evolution of ecosystems are mainly affected by anthropic factors, and ecological functions are mainly determined by the demands of human economic and social development. According to the classification of disturbance intensity, the human disturbance transition coefficients were determined (Table 2).

Based on the transition area and human disturbance conversion coefficient, the HTI was established to describe the stability of wetland utilization mode and

Table 1 Disturbance intensity and description of landscape types

Disturbance type	Landscape types	Disturbance intensity	Code
The spontaneous renewal	Natural forest land	1	N1
	Natural river	1	N1
The human-regulated	Reservoir	2	R1
	Artificial forest land	2	R1
	Artificial canal	2	R1
	Artificial lake	2	R1
	Grass land	3	R2
	Arable land	3	R2
	Pond	3	R2
The human-dominated	Mining subsidence wetland	4	D1
	Construction land	5	D2
	Unuseful land	5	D2

Table 2 Disturbance transition coefficients

Disturbance type	N1	R1	R2	D1	D2
N1	0	1	2	3	4
R1	− 1	0	1	2	3
R2	− 2	− 1	0	1	2
D1	− 3	− 2	− 1	0	1
D2	− 4	− 3	− 2	− 1	0

intensity (Qin & Zhang, 2021). We divided the human disturbance to wetlands into positive transitions and negative transitions. A positive transition (HTI<0) refers to a decline in the disturbance level. A negative transition (HTI>0) indicates an increase in the disturbance level, indicating a higher utilization intensity of wetlands. When the HTI is close to 0, it indicates that the disturbance level has not changed significantly.

$$HTI = \sum_{i=1}^{h} \left(S_{\ddot{y}}/S_A \right) \times h_{\ddot{y}} \tag{2}$$

where h_{ij} denotes the transition coefficient of ith disturbance level change to jth disturbance level, as shown in Table 3. The S_{ij} denotes the area of ith disturbance level change to jth disturbance level. The S_A denotes the total change area.

Results

Changes in wetland area and distribution

Human activities have a significant impact on wetland evolutionary processes at the landscape scale. In the study area, the total area of wetlands increased by 27.8% from 1991 to 2021, as shown in Fig. 3. Consequently, the wetland rate of the study area increased from 6.65 to 8.50%. The wetlands expanded periodically rather than continuously. From 1991 to 2000, the wetland area first decreased and then increased, and it was the same from 2005 to 2021. This process indicates that the human disturbance to wetlands fluctuated, and the intensity in every period was different. In the nonwetland landscape types, the most striking change was the reduction in arable land, with a decrease of 26.56% over the 30 years. However, arable land was still the largest land-use type in the study area, accounting for 46.1% of the total area in 2021. In contrast, construction land increased by 42.27%. Its share increased from 18.27% in 1991 to 25.99% in 2021, with the largest increase in the nonwetland landscape. From 1991 to 2021, the proportion of forestland increased from 10.62 to 15.96%, with an increase of 50.25% over 30 years. Grassland was the smallest but increased rapidly. The area of grassland in 2021 was 2.8 times that in 1991. Unused land has obvious instability. It decreased rapidly after reaching a maximum in 2015 but increased by 30.21% during the study period.

Figure 3 depicts the changes in the composition of wetlands in the study area from 1991 to 2021. The results demonstrate that artificial channels, mining subsidence wetlands, and natural rivers were the main wetland types in 1991, accounting for 33.24%, 30.28%, and 24.39% of the total area of wetlands, respectively. The total area of ponds, reservoirs, and artificial lakes only take up 12.09% of the total wetland area. The mining subsidence wetlands increased by more than 25% during the period from 1991 to

Table 3 Wetland transition area from 1991 to 2021 (ha)

Area	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020
WL to AL	679.47	227.63	484.58	609.04	437.00	278.68
WL to CL	489.75	232.68	676.17	684.56	174.14	129.89
WL to FL	12.20	21.96	8.82	28.01	69.21	127.32
WL to GL	5.40	1.46	31.51	93.33	41.80	121.68
WL to UL	402.71	224.63	100.29	280.09	412.67	10.07
AL to WL	754.51	1382.93	628.62	440.71	805.50	1177.01
CL to WL	370.11	474.92	289.18	424.58	485.41	216.62
FL to WL	25.54	6.07	58.65	15.36	43.55	78.53
GL to WL	0.40	0.02	31.94	26.25	40.45	39.62
UL to WL	104.14	367.09	295.56	127.98	221.37	271.89

WL refers to wetland; AL refers to arable land; CL refers to construction land; FL refers to forest land; GL refers to grass land; UL refers to unused land

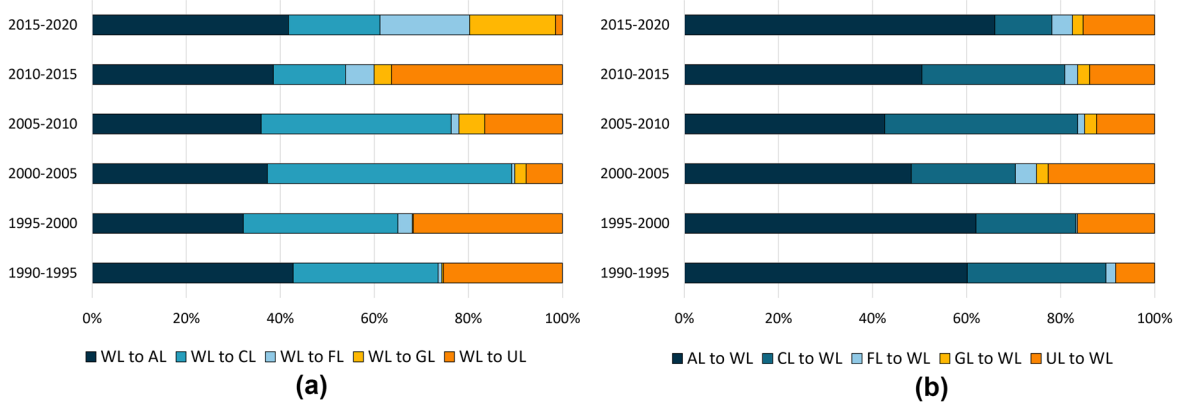**Fig. 3** Changes of wetland composition and wetland rate in Huaibei
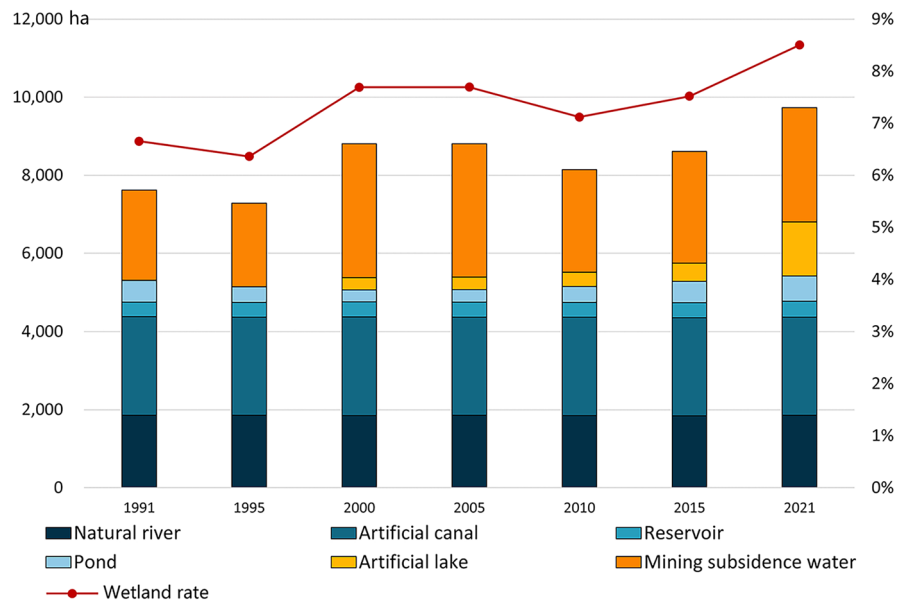
2021. In 2021, mining subsidence wetlands, accounting for 30.11% of the total wetland area, were the largest wetland type. The proportions of artificial canals and natural rivers decreased to 25.79% and 19.12%, respectively. Natural rivers and artificial canals were the most stable, with a changing rate of less than 1%. These results indicate that human disturbance had little impact on the landscape patterns of rivers. The reservoirs were mainly distributed in the hilly area in eastern Huaibei, with an increase of 11.11% during the whole study period. Prior to 2000, the area of ponds decreased, but after 2000, it increased. The pond area increased by 16.23% from 1991 to 2021. With a large number of mining subsidence wetlands being transformed into wetland parks, the area of artificial lakes increased the most. In 1991, artificial lakes only occupied 0.05% of the total wetland area, but it rose to 14.22% in 2021.

The growth and loss of wetlands in different periods were determined by using the land-use transition matrix (Table 3). The results demonstrated that during 1991 and 2021, a total of 2716.4 ha of wetlands was converted into arable land, accounting for more than 30% of the lost wetland area in each period, which was the main way of reducing wetlands (Fig. 4a). Due to land reclamation, mining subsidence wetlands were extensively converted to arable land. To encourage the ecological restoration of abandoned land in mining areas, the Land Management

Law proposed that local governments would obtain a specific percentage of construction land after mining wastelands were rehabilitated. Affected by this policy, a total of 2387.2 ha of mining subsidence wetlands has been converted into construction land in the past 30 years, mainly in the eastern and south-eastern parts of the city. In recent years, the area of mining subsidence wetlands converted into artificial forest and grassland has gradually increased. The process of ecological restoration in mining subsidence wetlands is long-term and includes the discharge of water and the filling of subsidence pits. Temporary unused land should appear during this period.

Figure 4b shows that the increased wetlands were mainly from arable land and construction land. From 1991 to 2021, a cumulative 5189.29 ha of arable land was converted into water area. In each period, the area converted from arable land into wetland occupied more than 40% of the increased wetlands. This result indicated that large amounts of arable land changed to mining subsidence wetlands due to mining activities. In the two periods of 1991–1995 and 1995–2000, more than 60% of the increased wetlands were converted from arable land. From 2000 to 2015, the proportion decreased, indicating that the damage intensity of mining to arable land decreased. From 2015 to 2021, this proportion increased to 65.99%. Mining activities also resulted in the conversion of a number of rural residential areas and roads into

2015-2020
2010-2015
2005-2010
2000-2005
1995-2000
1990-1995

0%　20%　40%　60%　80%　100%

■ WL to AL　■ WL to CL　■ WL to FL　■ WL to GL　■ WL to UL

(a)

2015-2020
2010-2015
2005-2010
2000-2005
1995-2000
1990-1995

0%　20%　40%　60%　80%　100%

■ AL to WL　■ CL to WL　■ FL to WL　■ GL to WL　■ UL to WL

(b)

Fig. 4 Transition of the increased and lost wetlands in different periods. **a** The transition of wetlands into other landscape types; **b** the transition of wetlands from other landscape types

mining subsidence wetlands. During the study period, a total of 2260.8 ha of construction land was converted into wetlands, less than arable land. Unused land was also an important part of the increased wetlands. During the study period, a total of 1388.02 ha of unused land was converted into wetlands, which were mainly abandoned land in the mining area. It can be concluded that the main reason for the wetland expansion in the study area was the subsidence of arable land, construction land, and abandoned land into water areas.

Changes in wetland landscape metrics

Figure 5 presents the results of the landscape metrics at the landscape level. The trends of NP and PD were consistent. The NP of wetlands increased from 521 in 1991 to 1241 in 2021. The increase in ponds and mining subsidence wetlands were the main reasons for the rise in the NP. Meanwhile, the PD of wetlands also rose from 0.07 to 0.13 from 1991 to 2021. The increase in NP and PD suggested that the wetlands in the study area have become more numerous and on average smaller and more vulnerable in the past 30 years. The LPI of wetlands increased gradually after 1991, reached a maximum in 2010, and then decreased gradually. This result demonstrates that the larger wetland patches gradually increased in the first 20 years. Conversely, the larger wetland patches began to be divided into smaller patches in the last decade. This result indicated that the dominance of wetlands declined with the recession of the mining

industry after 2010. The results of SPLIT and COHESION illustrated that the wetlands had the lowest SPLIT in 2000 and 2005, while COHESION was at a higher level. This result indicated that the connectivity was relatively high in this period. After 2010, the SPLIT of wetlands gradually increased, and the COHESION dropped rapidly, indicating that the connectivity of the wetland began to decline. The analysis results of PAFRAC illustrate that the PAFRAC of wetlands underwent a downwards trend from 1991 to 2021, implying that the form and edge of wetland patches tended to be regular and simpler as the level of human disturbance increased.

Landscape metrics at the class level allow a deep interpretation of the landscape features of different wetland types. Figure 6 presents the results of the landscape metrics at the class level. Over the past 30 years, both the ponds and mining subsidence wetlands had higher PD and showed an upwards trend. This result demonstrated that the ponds and mining subsidence wetlands had the highest fragmentation. The PD of artificial canals was lower than that of ponds and mining subsidence wetlands but relatively stable. The natural rivers, reservoirs, and artificial lakes had lower PD values, indicating that the habitat integrity of these wetlands was relatively high. The maximum MPA occurred in the reservoirs, varying from 70.98 to 95.74 ha. The artificial lakes had the largest change in MPA. In 1991 and 1995, the area of artificial lakes was very small, but with the transition of mining subsidence wetlands into artificial lakes, the MPA of artificial lakes increased rapidly
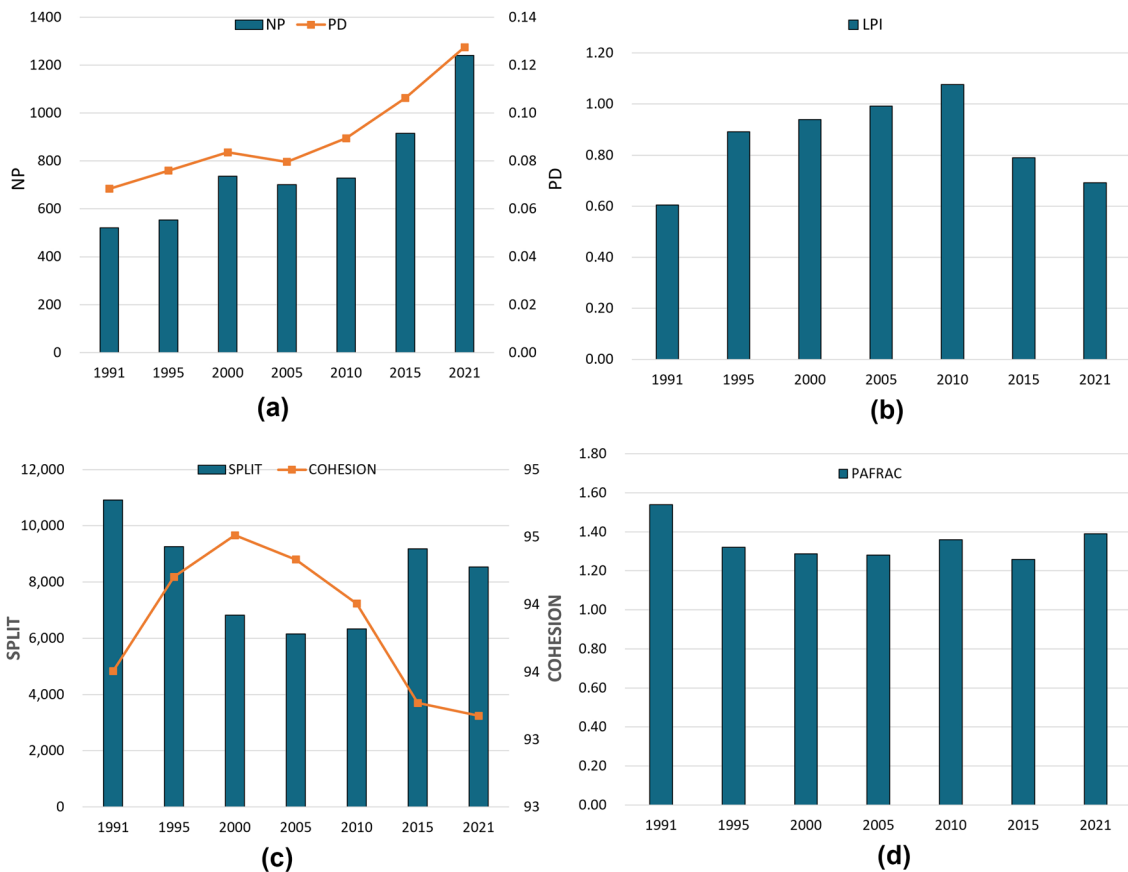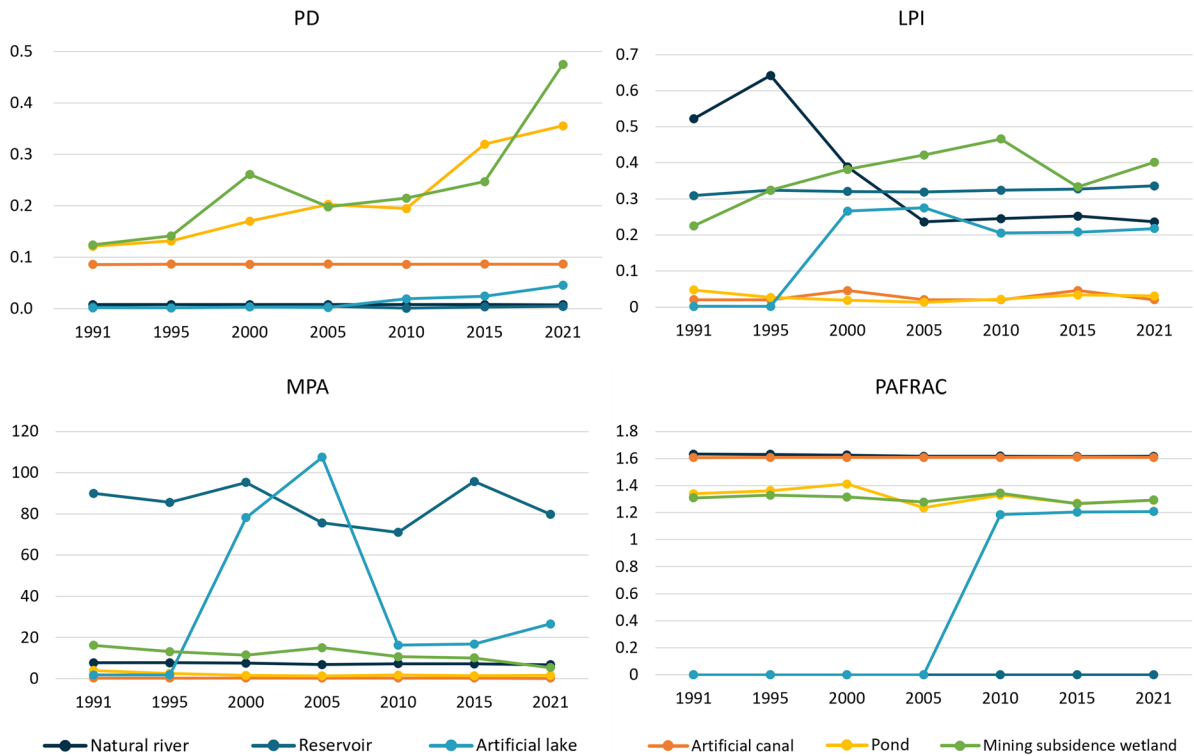
Fig. 5 The dynamic variation of landscape level landscape metric in north of Huaibei, during 1991–2021. **a** The NP and PD of wetlands. **b** The LPI of wetlands. **c** The SPLIT and COHESION of wetlands. **d** The PAFRAC of wetlands

and was only lower than that of reservoirs. The minimum MPA occurred in the artificial canals, indicating that the artificial canals were broken into small area patches. Figure 6 shows that the LPI of natural rivers was at a maximum in 1991, 1995, and 2000. However, the LPI of mining subsidence wetlands gradually increased and became the most dominant wetland type after 2005. Overall, the LPI range of mining subsidence wetlands, reservoirs, natural rivers, and artificial lakes decreased in 2021. This change indicated that the wetland evenness in the study area was improved. For the PAFRAC, as the shape of natural rivers and artificial canals was the most complex, their PAFRAC was higher than 1.5. The PAFRAC results of mining subsidence wetlands and ponds were between 1.2 and 1.5, indicating that the complexity of these two wetland types was similar. The

shape of the artificial lakes was relatively regular, which implied that the construction and management of artificial lakes were mainly dominated by human factors.

Spatiotemporal dynamics of human disturbance

Previous studies have proven that the stronger the human disturbance is, the higher the vulnerability of the ecosystem. Therefore, monitoring the changes in the intensity of human disturbance is important for identifying ecological risk areas. The HTI can be used to examine how human disturbance intensity is changing. From 1991 to 2005, the HTI results were positive and were 26.86 (1991–1995), 8.24 (1995–2000), and 16.93 (2000–2005). It was clear that the overall disturbance level to wetlands was rising, while the

Fig. 6 The dynamic variation of class level landscape metric in north of Huaibei, during 1991 to 2021

magnitude of change decreased in the first 15 years. From 2005 to 2010, the HTI decreased for the first time to -0.11. However, it rose again to 21.68 from 2010 to 2015. From 2015 to 2021, the disturbance level to wetlands sharply decreased, and the HTI was -62.61. This special change was closely related to the implementation of many wetland ecological restoration projects.

In this study, the wetland patches in which the human disturbance level changed were considered evaluation units. Then, the spatial variation in HTI in different periods was quantitatively analyzed. The natural fracture method was adopted to divide the HTI results of each period into 5 grades. The level I positive transition refers to the wetlands in which the human disturbance level significantly declined, and there was a slower decrease in the human disturbance level in the wetlands with a level II positive transition. A low transition refers to wetlands with relatively stable human disturbance levels. A level I negative transition refers to the wetlands in which the human disturbance level significantly rose, and there was a slower rise in the human disturbance level in

the wetlands with a level II negative transition. Figure 7 shows that the total area of positive transition wetlands was the smallest from 2010 to 2015, at 178.69 ha. The total area of positive transition wetlands in other periods varied from 500 to 700 ha. In each period, the area of level II positive transition wetlands was larger than that of level I positive transition wetlands. From 2015 to 2021, the area of level I positive transition wetlands was the largest, reaching 324.56 ha. This result indicated that the scale of wetland ecological restoration was the largest during this period. The area of low transition wetlands had the largest increase, which suggests that the implementation of wetland protection policies played an important role in restricting human disturbance and changes in wetlands. The total area of negative transition wetlands ranged from 800 to 950 ha during the four periods from 1991 to 2010. From 2010 to 2021, the total area of negative transition wetlands decreased significantly, ranging from 200 to 550 ha. The area of the level I negative transition wetlands underwent a significant decrease. The area of level II negative transition wetlands reached a maximum from 2005 to 2010
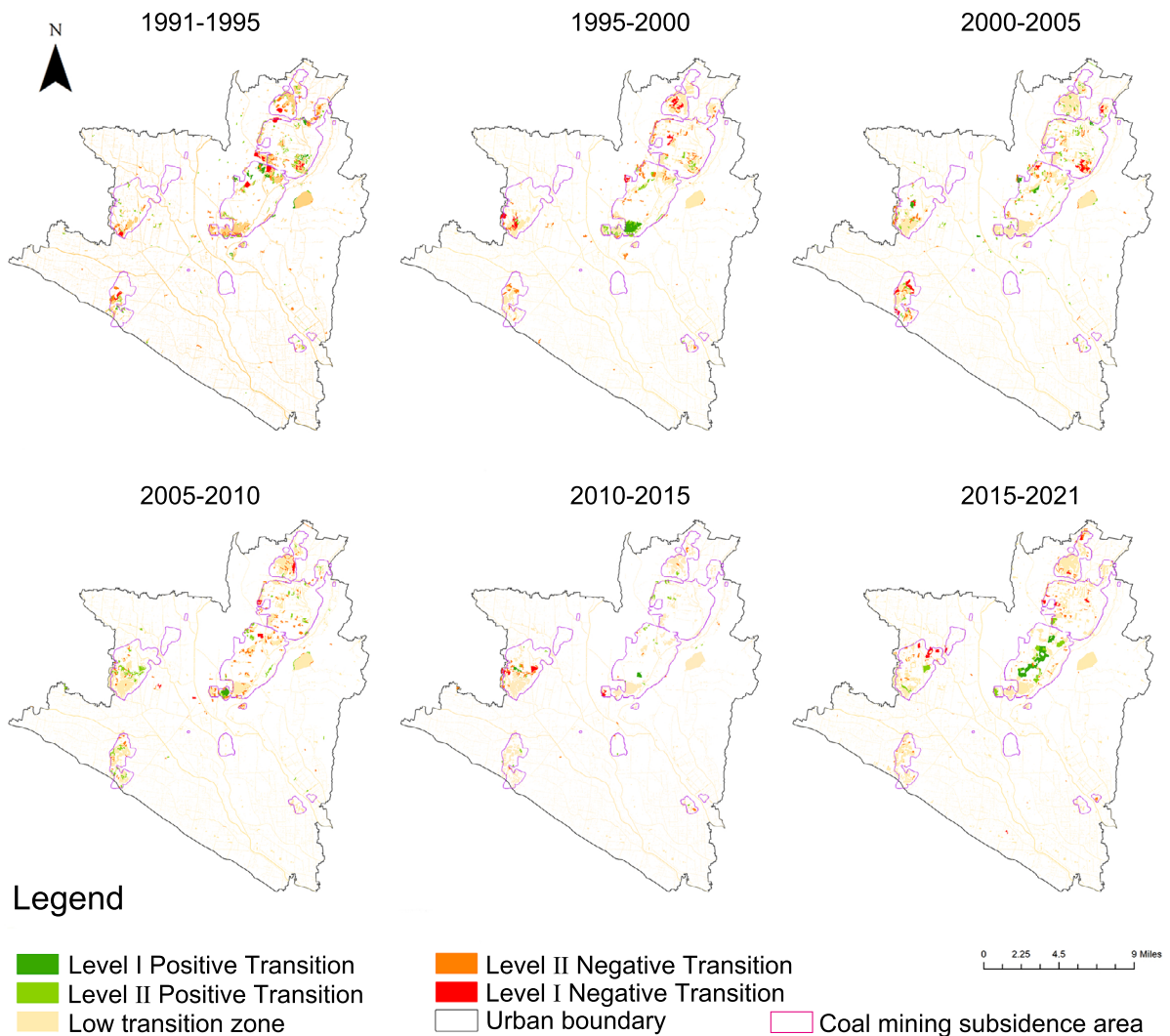
Fig. 7 Spatial distribution of HTI in the study area from 1991 to 2021

and then decreased significantly in the following two periods.

Figure 7 shows that there were obvious changes in the spatial distribution of the HTI in the study area. During the study period, the human disturbance level to natural rivers and artificial canals changed insignificantly. The reservoirs were also located in the low transformation zone. The HTI of reservoirs changed slightly, which was mainly affected by the change in water level. From 1991 to 2010, the negative transition wetlands were mainly around the northern mining subsidence areas with a trend of expansion. After 2010, with the closure of most coal mines in

the north, the area of negative transition wetlands decreased dramatically. Negative transition wetlands emerged in the Liuqiao mining area in the west. A large number of level II negative transition wetlands were also distributed around the city, mainly because some mining subsidence wetlands were transformed into construction land and unused land. In addition, due to the conversion of arable land to ponds, some level II negative transition wetlands were distributed in rural areas, and changing processes were discontinuous. The distribution of positive transition wetlands had an obvious phased difference. In 1995–2000, 2005–2010, and 2015–2021, the level I positive

transition wetlands were concentrated in the southern urban built-up areas. The main reason for this is that many abandoned lands had been restored to urban wetland parks. In other periods, the positive transition wetlands were scattered, mainly located within the mining area and adjacent to negative transition wetlands.

Correlation analysis of the landscape pattern index and HTI

Huaibei is a city that was established for coal mining. Consequently, human activities changed the landscape patterns in a unique way. To examine the relationship between the transformation of human disturbance level and landscape pattern variations, the Pearson correlation coefficient was used to determine the correlation between the HTI and the changing rate of landscape metrics (Cui et al., 2021). The grid method was used to reflect the spatial varieties of the wetland HTI. The moving window method was used to calculate the spatial varieties of the wetland landscape metrics. The analysis results include the following three aspects: (1) the correlation between the overall wetland HTI and the change in the wetland landscape metrics; (2) the correlation between the increase in the wetland human disturbance level (HTI > 0) and the change in landscape metrics; and (3) the correlation between the decline in wetland human disturbance level (HTI < 0) and the change in landscape metrics.

The results highlighted that in the study area, the changes in human disturbance level were positively correlated with the changes in wetland fragmentation, dominance, shape index, and connectivity (Table 4). The results of the correlation analysis between the HTI and PD and NP illustrated that the rise in the human disturbance level intensified the degree of wetland fragmentation. However, the decline in the human disturbance level had no obvious correlation with fragmentation. This indicates that the current wetland ecological restoration projects have not effectively improved the overall fragmentation of wetlands. The land subsidence

of the mining area in the study area led to the formation and expansion of a large number of waterlogged areas. Therefore, with the increase in the wetland disturbance level, the LPI of wetlands increased. Similarly, the change in LPI was unrelated to the decline in wetland disturbance level. In terms of the shape index, both the increase and decrease in the wetland disturbance level resulted in an increase in PAFRAC, which indicated that the greater the change in the human disturbance level was, the more complex the wetland shape. This is because the formation of mining subsidence wetlands was the main reason for the increase in the level of human disturbance. The mining subsidence wetlands appeared due to spontaneous waterlogging after the surface collapse. The formation mechanism was more similar to that of natural wetlands. The correlation between the HTI and the change in SPLIT in the study area illustrates that the rise in the human disturbance level led to an increase in wetland separation. The COHESION of wetlands in the study area also increased with the rise in human disturbance level, but the correlation was relatively low. This also suggests that the current wetland restoration projects have not effectively improved the connectivity of wetlands.

As can be seen from the results above, underground mining activities in areas with high groundwater tables have significantly disrupted the wetland landscape patterns. Land subsidence and waterlogging eventually led to the creation of wetland landscapes from a large amount of arable and construction land. Wetland area has rapidly increased due to human disturbance. At the same time, changes in the human disturbance level affected fragmentation, dominance, patch stability, and connectivity of wetland landscape patterns.

Discussion

In the mining cities with high groundwater level, the way and result of wetland landscape evolution affected by human activities have significant

Table 4 Correlation analysis of HTI and landscape index

Landscape index	PD/NP	LPI	PAFRAC	SPLIT	COHESION
HTI	0.485^{**}	0.359^{**}	0.527^{**}	0.227^{**}	0.085^{*}
HTI > 0	0.481^{**}	0.435^{**}	0.083^{**}	0.225^{**}	0.189
HTI < 0	-0.066	0.021	-0.387^{**}	0.516^{**}	-0.034

**Sig. < 0.01, *Sig. < 0.05

particularity. To reflect the sensitivity of wetland ecological structure and ecological risk on the landscape scale, it is important to analyze the changes in human disturbance intensity and the wetland landscape pattern's response process. Ecological restoration planning played an important role in optimizing the structure and function of the wetland ecosystem. Due to the instability of coal mining subsidence wetlands, many cities lacked the evaluation and planning of wetland spatial patterns at the landscape scale. In recent years, wetland ecological planning based on process restoration has gained a lot of attention.

In many cities, wetlands are at risk from human disturbance, including a reduction in area and quantity and habitat fragmentation (Jiang et al., 2014; Mondal et al., 2017). The main purposes of the wetland ecological compensation strategy were to recover the wetland rate and wetland ecological functions (Yan et al., 2022). However, in the mining cities with a high groundwater table, the total area of wetlands increased under the influence of human disturbance. Taking the study area as an example, the wetland area has increased by 27.8% in the past 30 years due to human disturbance. The proportion of natural wetlands and artificial wetlands changed from 24.39:75.61 in 1991 to 19.12:80.88 in 2021. The proportion of natural wetlands sharply decreased. The mining subsidence wetland has become the largest wetland type in the study area. The ecological, economic, and social effects in these cities were very special (Howladar, 2013). Most of the mining subsidence wetlands were isolated with low connectivity. The hydrology and nutrient and biological cycles of wetlands were incomplete (Zhang et al., 2020). Therefore, the ecological functions in regulating floods, maintaining biodiversity, and conserving water were weak. However, the formation of mining subsidence wetlands played an obvious role in improving habitat diversity and had important potential ecological value. In addition, the expansion of mining subsidence wetlands has led to the destruction of arable land and rural residential areas, and a large number of farmers have lost their land. So it is necessary to use mining subsidence wetlands to develop green agriculture, tourism, and other continuous industries to alleviate the social conflicts arising from the limitation of land use. In this context, balancing wetland ecological health and sustainable economic and social development has become an important part of wetland ecological restoration plans for such cities.

The shrinkage of wetlands could lead to fragmentation of habitats, reduction of landscape dominance and connectivity, and even degradation of ecological functions (Jiang et al., 2014; Zheng et al., 2019). However, less attention has been given to the impact of wetland expansion on landscape patterns. The distribution of mining subsidence wetlands was determined by the spatial distribution of coal mines. The increase in wetland area may not improve the ecological security patterns of wetlands. The analysis of wetland landscape patterns in the study area illustrated this result. With the increase in wetland area, fragmentation also increased, and the mean patch size decreased. From 1991 to 2010, the separation degree of wetlands decreased. After 2010, although the wetland area continued to increase, the separation degree increased, and the aggregation degree decreased. Therefore, wetland ecological restoration planning should consider the optimization of the overall wetland ecological network. Due to the instability of wetland landscape patterns, future changes in wetlands should be predicted according to the hydrological conditions and coal mining conditions in wetland ecological network planning (Gong et al., 2015). On this basis, the wetland landscape patterns could be rationally planned by identifying important ecological patches and corridors.

Accurately reflecting the intensity and changing patterns of human disturbance is an important basis for identifying ecological risks and repairing the ecological environment (Gaglio et al., 2017; Londe et al., 2022). In the mining cities with a high groundwater table, the rise in the human disturbance level in wetlands was mainly affected by mining activities and the expansion of construction land. The decline in the human disturbance level was mainly affected by farmland reclamation and the construction of wetland parks. In China, the existing mining technology in built-up coal mines has difficulty avoiding land subsidence; so the disturbance of mining activities to wetlands will continue. How to reduce the duration of high disturbance has been the focus of ecological restoration in mining areas. Mining subsidence includes pre-subsidence, dynamic subsidence, and residual subsidence. Ecological restoration methods include pre-restoration, process restoration, and post-subsidence restoration. Pre-restoration decreases the impact of land subsidence on wetlands through filling mining, strip mining, and other mining technologies.

However, this method is mainly applied to new coal mines. Post-subsidence restoration involves ecological restoration after the land is stabilized, which would result in the long-term abandonment of mining subsidence wetlands. Based on the simulation of land subsidence and waterlogging processes, process restoration accurately chooses the timing and scope of ecological restoration and repairs the terrain and hydrological cycle of the subsidence area step by step. In the planning of wetland ecological restoration, the process restoration method has become the focus of restraining human disturbance (Liu et al., 2021). Lvjin Lake, the largest wetland park in the study area, is a typical case of process restoration. In addition, urban sprawl is another important type of human disturbance. On one hand, many wetlands have been converted into construction land. However, the sprawl of urban areas has also provided funds and opportunities for wetland ecological restoration. To improve the urban ecological environment, a large number of mining subsidence wetlands have been restored to wetland parks, which have been the fastest-growing wetland type in recent years. As such, rational planning of construction land and wetlands to avoid secondary disturbance to the restored wetlands is the focus of wetland ecological restoration.

This study focuses on analyzing the relationship between human disturbance changes and wetland landscape evolution in the mining cities with high groundwater tables. It cannot be ignored that natural factors such as climate, groundwater, and surface flows are also important driving forces affecting the evolution of wetland landscape patterns (Walz & Stein, 2014; Middleton, 2017). However, natural factors are stable over a certain period of time. In the study area, the impact of natural factors on wetlands was mainly reflected in seasonal changes and long-term cumulative effects.

Conclusions

This paper makes efforts to the human disturbance changes and landscape patterns response characteristics of wetlands in mining cities with high groundwater tables. The research results suggest that the landscape evolution of wetlands in these cities is distinguishable from that of other cities. In the study area, human activities have gradually increased the area of wetlands. The proportion of constructed wetlands has increased significantly. As such, the fragmentation of wetlands was more serious. The connectivity of wetlands first increased and then decreased over 30 years. The correlation analysis between the HTI and landscape metrics illustrated that the current wetland ecological restoration planning has not effectively improved the fragmentation and connectivity of wetlands. So that planning should propose the overall strategy and phased optimization objectives of wetland landscape patterns optimization according to subsidence prediction. Wetland ecological restoration planning needs to coordinate wetland ecological security, urban sprawl, and land reclamation. Wetland ecological restoration should reduce the wasted time of mining subsidence wetlands as much as possible and avoid repeated disturbances to wetlands. In addition, wetlands, forestland, and grassland together constitute the ecological barrier of the cities. To improve the service function of the integrated ecosystem, it requires urgent attentions from local planning authorities, policy makers, and academical scholars and engages the publics to develop an advanced ecological network planning in comprehensive hierarchy. So as to enhance the integrity of the regional ecosystem by optimizing the relationship between wetlands and other types of landscapes.

Data availability The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request. All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Declarations

Competing interests   The authors declare no competing interests.

Conflict of interest   The authors declare no competing interests.

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